

# Multipulse Addressing of a Raman Quantum Memory: Configurable Beam Splitting and Efficient Readout

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Quantum memories are vital to the scalability of photonic quantum information processing (PQIP), since the storage of photons enables repeat-until-success strategies. On the other hand, the key element of all PQIP architectures is the beam splitter, which allows us to coherently couple optical modes. Here, we show how to combine these crucial functionalities by addressing a Raman quantum memory with multiple control pulses. The result is a coherent optical storage device with an extremely large time bandwidth product, that functions as an array of dynamically configurable beam splitters, and that can be read out with arbitrarily high efficiency. Networks of such devices would allow fully scalable PQIP, with applications in quantum computation, long distance quantum communications and quantum metrology.

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Quantum information processing promises radical new technologies, such as provably secure communications [1], enhanced sensors [2], and exponential computational speed ups [3]. Photonics offers a powerful platform for quantum processing, with interactions between optical modes mediated by beam splitters. However, logical operations are conditioned on measurements [4], with the consequence that all photonic quantum information processing (PQIP) schemes are probabilistic. The scalability of PQIP therefore depends critically on bringing two technologies to maturity. First, optical quantum memories [5], capable of storing the successful outputs of quantum gates for many clock cycles, are required to synchronize the nondeterministic elements of a PQIP network. Without memories the success probability of a photonics processor drops exponentially as its size increases. Second, compact and reconfigurable photonic circuits [6,7], comprising low-loss beam splitters and active switching, will be vital to the construction of complex PQIP architectures.

In this Letter, we demonstrate that a Raman quantum memory can serve as a temporal-mode-selective beam splitter. This means that all elementary operations needed for scalable PQIP are accessible in a single device. In particular we show that addressing the memory [8] with a train of control pulses produces an interaction that is formally identical to a dynamically configurable network of optical beam splitters. Recent results have established the coherence of this interaction for the case of photon-echo Raman memories [9,10]. In the present work, we use a broadband Raman memory protocol [11] with a time-bandwidth product—the ratio of storage time to pulse duration—in excess of 1000. In this regime, multiple independent readout pulses can be used to trigger a train of

read events. This allows us to distribute photons over many temporal modes with controllable amplitudes, and, furthermore, to extract excitations stored in the memory with arbitrarily high efficiency. By interfering the multipulse output from two independent memories, we verify that the interaction preserves coherence across all time bins, which is the prerequisite for phase-sensitive multiplexing of a photonic quantum network. The combination of storage and programmable coherent coupling in a single device makes the Raman memory a universal primitive component for PQIP.

As an example, consider the task of photon subtraction [12,13], which is a canonical non-Gaussian operation in continuous-variables (CV) quantum information protocols [14]. Traditionally, one half of a two-mode squeezed state is directed through a highly transmissive beam splitter. When a photon is detected at the reflected port, the transmitted joint state is no longer Gaussian, and is more entangled. However, the detection probability is small, so that many squeezed states must be prepared to achieve success. On the other hand, if one half of a squeezed state is stored in a Raman memory, a train of weak read pulses—corresponding to multiple beam splitters—allows us to repeat the protocol until success (that is, until the emission of a photon from the memory is detected). This application permits a doubly exponential enhancement in the resource efficiency of CV entanglement distillation [15].

Storage in atomic ensembles allows strong light-matter coupling without the need for high-finesse cavities [16,17]; furthermore multiple spatiotemporal modes [18–22], or multiphoton (i.e., CV) states [23,24] can be stored. It has recently been shown that off-resonant Raman memories can also operate with quantum-limited

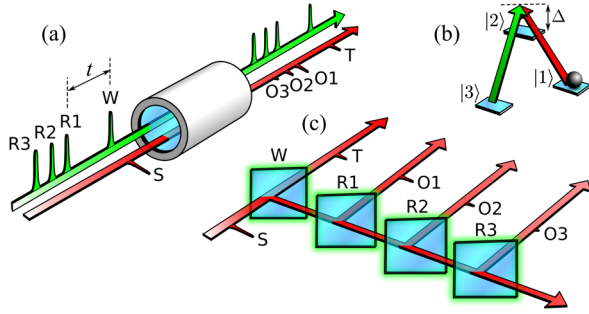


FIG. 1 (color online). (a) Raman memory: an incident signal  $S$  is directed through a Cs vapor cell along with an orthogonally polarized “write” control pulse  $W$ , followed by a series of “read” pulses  $R1$ – $R3$ . The unstored portion  $T$  of the signal is transmitted through the memory, while the retrieval pulses extract outputs  $O1$ – $O3$ . (b) Lambda-type level structure of the Cs atoms: atoms are prepared in  $|1\rangle$  (gray sphere). The signal (red) is blue detuned from the excited manifold  $|2\rangle$  and is coupled to the storage state  $|3\rangle$  via the Raman-resonant control (green). (c) Beam splitter network equivalent to (a).

noise in room temperature vapors [11,25], since collisional fluorescence [26,27] is eliminated. This off-resonant suppression of spontaneous emission makes Raman storage suitable for PQIP applications, and it also means that the atom-light interaction is unitary, so that via the Bloch-Messiah reduction [28,29] it is formally isomorphic to a sum of independent beam splitter transformations [30,31]. Essentially, Raman memories behave like beam splitters because the “failure mode” is transmission: light that is not stored exits the memory unattenuated, since there is no resonant absorption. Similarly, a stored excitation—a spin wave—that is not retrieved simply remains in the memory, since no population is transferred to the excited state. Our far off-resonant memory has a  $>$ GHz acceptance bandwidth, meaning that we are able to store, and subsequently address the memory with, many short optical pulses within the  $\sim \mu$ s decoherence time of the memory. In this Letter we show how to utilize this large time bandwidth product ( $\geq 1000$ ) to implement complex and configurable linear optical networks by temporal multiplexing with a train of readout control pulses [as represented in Figs. 1(a) and 1(c)]. We demonstrate that a stored excitation can be completely retrieved, with efficiency arbitrarily close to unity, with such a train of pulses. Finally, we verify that coherence is preserved across temporal modes by interfering signals retrieved from two independent memories.

Our quantum memory is based on Raman absorption in a warm vapor cell (62 °C, 7 cm long) containing cesium and 20 Torr of Ne buffer gas [shown schematically in Fig. 1(a)]. The Cs atoms are prepared in their ground states  $|1\rangle$  ( $6^2S_{1/2}$   $F = 4$ ) via optical pumping with a diode laser at 852 nm (150  $\mu$ W, beam waist 350  $\mu$ m). The signal field

to be stored (pulse duration 300 ps) is tuned away from the atomic resonance  $|2\rangle$  ( $6^2P_{3/2}$ ) by a large detuning  $\Delta = 15$  GHz but is coupled to the long-lived 9.2 GHz hyperfine-shifted storage state  $|3\rangle$  ( $6^2S_{1/2}$   $F = 3$ ) by a bright control pulse (also 300 ps), which is tuned into two-photon resonance with the signal [see Fig. 1(b)]. After some delay  $t$  chosen by the user, subsequent control pulses convert the spin wave back into optical signals.

We model the effect of applying multiple readout pulses using a linearized, adiabatic theory of Raman storage developed previously [8,30]. Given an initial input pulse with profile  $A_{\text{in}}(\tau)$ , the spatial distribution of excitations in the memory is given by the spin wave amplitude

$$B_{\text{out}}(z) = \int K_s[\Omega_s(\tau); \tau, z] A_{\text{in}}(\tau) d\tau, \quad (1)$$

where  $K_s$  is an integral kernel involving a Bessel function [8,30]. The argument  $\Omega_s(\tau)$  is included to indicate the explicit dependence of  $K_s$  on the temporal shape of the control pulse used to store the signal field. For readout, the retrieved signal field is given by a similar formula,

$$A_{\text{out}}(\tau) = \int K_r[\Omega_r(\tau); z, \tau] B_{\text{in}}(z) dz, \quad (2)$$

where  $K_r$  is similar to  $K_s$ , and where  $\Omega_r$  now describes the time dependence of the control field used to retrieve the stored spin wave. As shown in [30,31], singular value decomposition of these kernels provides a set of optical or spin wave modes that are independently coupled by effective beam splitter interactions, where the reflectivity is set by the energy in the control. Here, we comment that the shapes of these optical modes are determined by the shape of the control pulse [32]. Generally only one pair of optical or spin wave modes is efficiently coupled by the interaction [30], so that the memory can be used as a coherent nonstationary mode filter [33,34], selectively extracting an arbitrary mode from a pulse, storing it, and releasing it with an arbitrarily chosen shape. This has applications in multimode quantum communications [35] and nonlinear photonic gates [36]. In the case of multipulse retrieval,  $\Omega_r$  has the form of a train of pulses. One may therefore equally characterize the retrieval process either as a single time nonstationary, “active,” beam splitter interaction [34] that maps the spin wave to a mode that is distributed over several time bins, or as a series of more conventional beam splitters, as depicted in Fig. 1(c).

In general, we have that  $B_{\text{in}}(z) = \kappa B_{\text{out}}(z)$ , where  $\kappa < 1$  is a constant representing decay of the spin wave amplitude through decoherence over the storage time. We experimentally determine the temporal profiles  $A_{\text{in}}$ ,  $\Omega_{s,r}$  by taking square roots of the traces measured using a fast photodiode (see below). This assumes flat phase for all pulses, an assumption which is confirmed by autocorrelation measurements demonstrating a transform-limited laser output.

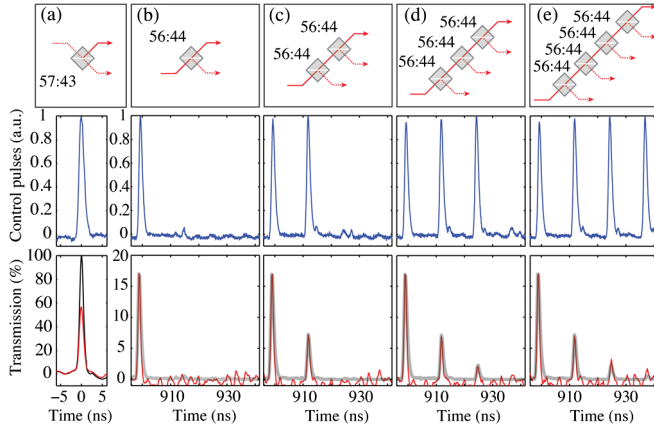


FIG. 2 (color online). Multiple retrieval. Blue lines: Control field pulses. Black line: Incident signal field. Red lines: Transmitted or retrieved signal pulses. Thick gray lines: Theoretically predicted retrieved signals. (a) Storage (efficiency 43%). (b)–(e) Multiple retrievals (efficiencies: 17%, 7.5%, 3%,  $\approx 1\%$ ). Top panels: Analogous beam splitter networks. Storage and retrieval efficiencies are subject to an error of  $\pm 0.5\%$  [8,11].

To implement multipulse readout, we use a Pockels cell (Quantum Technology Starfire 5DR) to select a series of consecutive pulses (energy  $\sim 10$  nJ) separated by 12.5 ns from the 80 MHz pulse train of the laser (Newport Tsunami). We store a weak signal pulse (a coherent state containing around 1000 photons), frequency shifted from the control by means of a 9.2 GHz electro-optic modulator (Newport 4851-M), and observe the transmitted and retrieved pulses on an amplified avalanche photodiode with a ns response time (Thorlabs APD210). Figure 2 shows the successive retrieval of between 1 and 4 pulses; the agreement with theory is excellent. The model predicts that each read pulse should extract roughly  $\eta \approx 56\%$  of the stored spin wave, and this explains the observed efficiencies correctly, after accounting for decoherence of the spin wave by  $\sim 30\%$  ( $\kappa \approx 0.7$ ) over the 900 ns storage time, which is due mostly to the influence of stray magnetic fields [11].

The combined retrieval efficiency of four read pulses is  $95 \pm 2\%$ , consistent with the theoretically predicted efficiency  $(1 - \eta)^4 \approx 96\%$ , which demonstrates how unit retrieval efficiency is rapidly approached with a multipulse read sequence. The efficiency of an ensemble memory is generally limited by the achievable resonant optical depth, whether or not the protocol operates on resonance [37–39], but here this number exceeds 1000 [11] and is not a limiting factor, which is why unit efficiency can be reached.

In general, partial storage is useful as a means to entangle optical and material modes. Also, nondeterministic storage can be heralded by postselecting those events where no light is transmitted through the memory. By contrast, inefficient retrieval from the memory is always detrimental, since all protocols involving memories

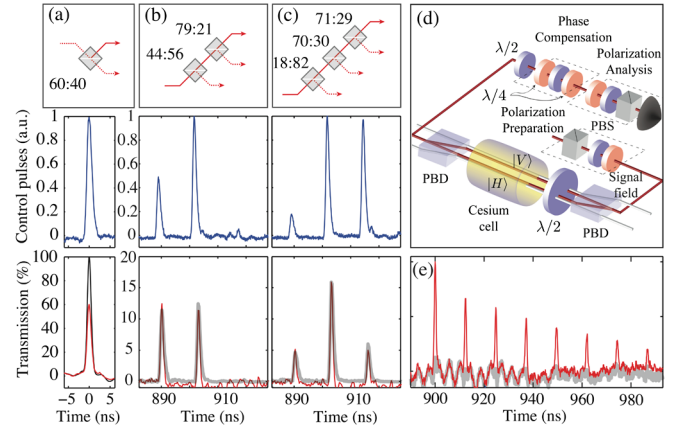


FIG. 3 (color online). Shaping and coherence of the readout. Color coding in parts (a)–(c) is the same as in Fig. 2. (a) Storage (efficiency 40%). (b) Balanced readout (efficiency 12.4% each). (c) Pyramidal readout (efficiencies: 5%, 16%, 5%). Storage and retrieval efficiencies are subject to an error of  $\pm 0.5\%$  [8,11]. Top panels show analogous beam splitter networks. (d) and (e): Coherence of multipulse readout demonstrated by interference between two pulse trains retrieved from independent memories. Top panel: Experimental layout. PBD: polarizing beam displacer; PBS: polarizing beam splitter.  $\lambda/2$ ;  $\lambda/4$ : half-wave and quarter-wave plates. The “phase compensation” wave plates correct for birefringence in the interferometer. Bottom panel: constructive and destructive interference across the entire multipulse retrieval: the incident signal is prepared with diagonal polarization and is split equally between the two memories. We analyze the retrieved signals in either diagonal (red) or antidiagonal (gray) polarizations.

eventually require that stored excitations are read out. Therefore the ability to completely retrieve the stored state, with arbitrarily high efficiency, using multipulse retrieval, is an important capability of the Raman memory.

Besides efficient retrieval, adjustment of the readout sequence enables control of the distribution of the retrieved signal over the readout modes. As discussed above, the theoretical model of the Raman interaction has the form of a collection of independent beam splitter transformations with effective reflectivities determined by the control field [30,31]. To further test the assertion that our memory can be described by this model, and to demonstrate the configurability of the beam splitter reflectivities, we varied the intensity distribution of the read control pulses by adjusting the Pockels cell timing.

The close agreement between experiment and theory in Fig. 3 confirms that the interaction can indeed be described as a beam splitter interaction between optical and material modes. These data also demonstrate the shaping of a stored signal pulse into multiple retrieved signals in different time bins [32], which approach offers a straightforward path to generating time-bin entanglement. For instance, although here we stored coherent states, storage of a single photon, followed by partial retrieval using three read pulses would create a time-bin entangled  $W$  state [40], in which the



retrieved signal photon is distributed over three temporally distinct modes.

Finally, we tested the coherence of the interaction across multiple time bins by interfering the output of two independent memories [41]. To do this, we inserted the vapor cell into a passively stable Jamin-Lebedev interferometer (a polarization Mach-Zehnder), and illuminated each arm with optical pumping and control pulses, creating a pair of parallel, independent memories, whose output could be interfered by observing signals in the diagonal polarization basis. Figure 3(e) shows that we achieve near complete destructive interference across an eight-pulse retrieval, which is possible only if local phase fluctuations do not erode the memory coherence during multipulse readout. This property is critical for both the generation and preservation of quantum correlations within a photonic processor.

In summary, we have demonstrated that a far off-resonant Raman memory can serve both as a high bandwidth storage device and as a programmable and actively tuneable beam splitter array. We used a train of control pulses to distribute a stored excitation among multiple time bins with adjustable amplitudes; we showed that near perfect retrieval efficiency can be achieved with the use of just four read pulses, and we demonstrated that phase coherence is preserved in the memory across all time bins. Devices based on this interaction could form the core of a scalable platform for PQIP, enabling fast and reconfigurable quantum networking with in-built storage.

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